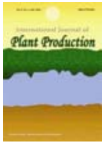

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Spatio-temporal variation of wheat and silage maize water requirement using CGMS model

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Abstract

The Crop Growth Monitoring System (CGMS) has been applied for spatial biophysical resource analysis of Borkhar & Meymeh district in Esfahan province, Iran. The potentially suitable area for agriculture in the district has been divided into 128 homogeneous land units in terms of soil (physical characteristics), weather and administrative unit. Crop parameters required in the WOFOST simulation model for winter wheat and silage maize, have been calibrated based on experimental data from the study area. The study area has been classified into three cropping calendar zones based on average annual temperature, altitude and latitude. For each zone, a sowing date has been defined for each crop as the starting point of crop growth simulation. Growth of these crops has been simulated for the potential situation in each land unit for 20 years of historical daily weather data. Daily potential evapotranspiration and irrigation requirements of each crop per land unit have been calculated in a post-simulation, on the basis of model outputs. Outputs of the model are crop yield (marketable yield and total biomass) and irrigation requirements per decade. Spatial and temporal variation in irrigation requirements has been analyzed. The temporal variation in crop water requirements is larger than the spati3al variation.

Keywords: Crop growth simulation; Spatial yield analysis; Potential yield; Water-limited yield; Water requirement; CGMS; WOFOST.

Introduction

Biophysical resource analysis is an essential part of agricultural planning and policy formulation. What is the potential of the resources, how they are used and could be used, should be determined in the resource analysis. For this purpose, biophysical resources such as soil and weather have to be analyzed in relation to crop performance. Quantitative analysis of biophysical resources can be carried out at different spatial scales such as plot, farm, regional and global (Van Keulen, 2007). In many developing countries, natural resources are overexploited by farmers (Lal, 2009), of which the effects are aggravated by drought and climate change and leads to a decline in their quality and quantity. Therefore, there is a need to identify appropriate land use activities and required inputs for sustainable agricultural production.

Spatial and temporal variations in the biophysical resources cause variations in crop production and input requirements that are important for agricultural planners and policy makers. For instance, potential crop yields and crop water requirements are dependent on weather and soil characteristics that are variable in time and space. Climate change is another issue which has impacts on potential crop yield and water requirement. Analysis of historical weather data in five weather stations in Iran during the maize growing season showed a general trend of increasing in maximum and minimum temperature (Gholipoor and Sinclair, 2011). Simulation models for crop growth are tools that can be used for estimation of yields, crop water requirements and fertilizer requirements in different situations (Van Ittersum et al., 2003) as well as climate change scenarios.

Crop growth simulation models quantitatively describe the effects of crop, soil and weather characteristics and management factors and their interactions in a simplified manner. Such models can be used to analyze effects of environmental conditions, such as climate, management and crop characteristics on crop yield and water productivity (Richter and Semenov, 2005; Basso et al., 2007; Kalra et al., 2007; Wu, 2008).

At present, statistically derived averages of crop yields and agricultural inputs are being used in the planning procedures in Iran. Combinations of GIS techniques and crop growth simulation models provide opportunities for spatial analyses of biophysical resources and estimation of crop yields (Badini et al., 1997; Wu et al., 2006). In this study, CGMS (Crop Growth Monitoring System) (Van Diepen et al., 2004) is used for spatial and temporal assessment of crop yields. The system includes a spatial crop growth simulation model that calculates potential and water-limited yields at different ‘points’ in the study area, based on weather, soil properties and crop characteristics.

The aim of this paper is to apply agro-ecological models to determine potential water requirements of winter wheat and silage maize for all land units in a certain region. The results are used to quantify the technical coefficients in agricultural planning models that are being developed to support goal and policy formulation for agricultural development in Borkhar & Meymeh district, Iran. Borkhar & Meymehdistrict is one of the districts in the northwest of Esfahan province in Iran. The district covers a total area of 762,500 hectares, of which about 37,000 is cultivated (on average: 22,000 ha with field crops, 2,000 ha fruit trees and 13,000 ha fallow). Most of the agricultural area is located in the southern part of the district. Average daily temperature in the study area varies between -2 ^{o}C in winter and 30 ^{o}C in summer. Annual precipitation varies between 100 and 300 mm over the district, concentrated in the winter months from December to April and average annual potential evapotranspiration is around 1400 mm.

Methodology

The general outline of the methodology is presented in Figure 1. First, the area potentially suitable for agriculture is determined based on the results of the land evaluation study, the current land use map and satellite images. The potential area for agriculture is then classified into homogeneous units (Elementary Mapping Units, EMU) in terms of biophysical conditions and administrative region. Administrative units have been recognized because results of this sort of researches and methodology, is useful and applicable for the managers who implement the appropriate agricultural policies inside an administrative area like district or sub-district. Quantitative spatial estimation of crop yield and water requirements are carried out for the winter wheat and silage maize in Borkhar & Meymeh districtusing CGMS. The software package of CGMS which was used in this study has been developed based on two point-based crop growth simulation models, WOFOST (Boogaard et al., 1998) and LINGRA (Bouman et al., 1996). CGMS comprises four main levels of processing: data preparation (level 0), weather data interpolation (level 1), crop growth simulation (level 2) and statistical evaluation of the results (level 3). Yield forecasting can be carried out at level 3 by comparison of outputs of level 2 with statistical data. Level 3 of CGMS has not been used in this study.

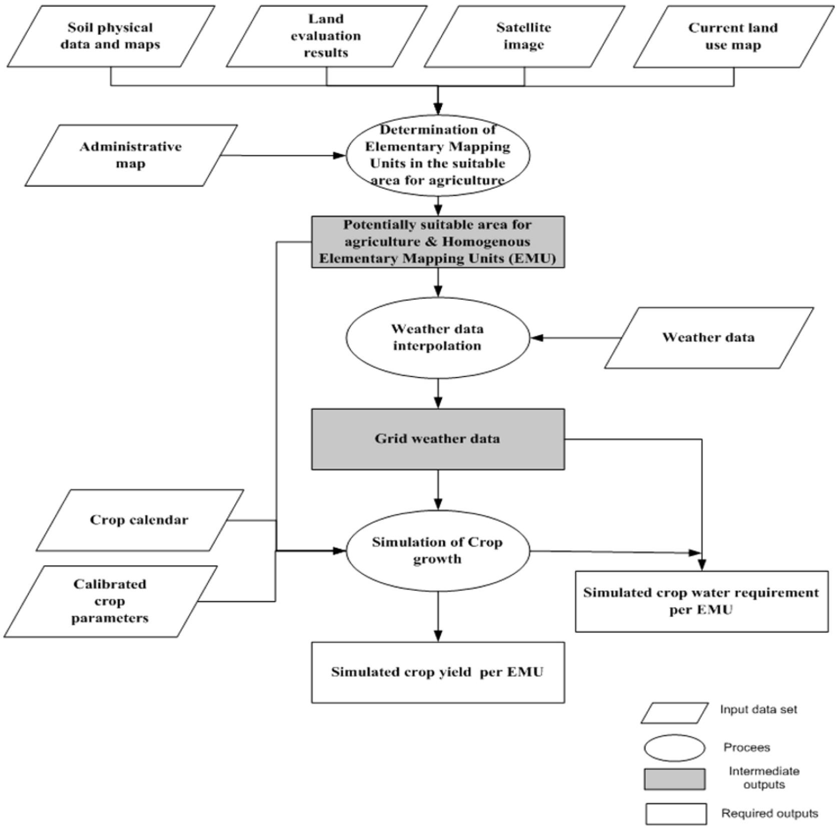


Figure 1. Schematic representation of the applied methodology.

At level 0, the required data for crop growth simulation such as soil, weather and crop data and also information on EMUs are stored in the specified formats in a database. Elementary Mapping Units are created by overlaying soil mapping units (SMU), grid weather and an administrative map. SMUs are delineated based on soil maps, taking into account soil physical characteristics in the potentially suitable area for agriculture. The area suitable for agriculture is identified from the land evaluation study and the potentially suitable area for agriculture is determined by adding currently cultivated land, not included in the suitable area of the land evaluation study. A weather grid, either regular or irregular, is defined as a spatial unit assumed to be homogeneous in terms of weather (Van der Goot et al., 2004). The village map (47 villages) in the sub-district is determined based on Thiessen polygons (Thiessen and Alter, 1911), as the administrative borders were not identified in the available maps. Weather grids and village polygons (administrative units) are considered identical to reduce the number of units. Hence, weather within a village is assumed constant. The procedure for generating EMUs results in creation of several very small units. To reduce the number of EMUs to a manageable entity, these small units (less than 50 ha) were merged with larger units, throughi) Merging the unit with the neighboring unit with the longest shared border and ii) merging isolated units with the largest unit in the village. Finally 128 EMU's were identified. In this study, an 8-digit code was assigned to each EMU, composed of a 4-digit code for the village and another 4-digit code for the SMU.

For application of WOFOST and CGMS to a specific combination of crop (variety) and environment, the model should be calibrated (Van Dam and Malik, 2003). Site-specific experimental field data are necessary for model calibration. Crop parameters of winter wheat is calibrated and validated based on field experiments in the years 2000-2001, 2003-2004 and 2004-2005 for winter wheat (cultivar M-73-18) in the agro-meteorological research center in Kaboutar Abad, close to the study area. Phenological stages, weed infestation, plant density, yield and yield components at harvest time were recorded in these experiments. Calibration has been carried out in two steps. First, phenological stages (time of flowering and maturity) have been calibrated based on daily weather data. In the second step, some of most sensitive crop parameters (Bessembinder et al., 2003) such as specific leaf area, light use efficiency, maximum relative increase in leaf area index and maximum leaf CO_2 assimilation rate have been calibrated. Different combinations of values, within the acceptable ranges for the parameters, were used iteratively on the basis of comparison of simulated and observed crop yields. Crop parameters from the literature (Van Heemst, 1988; Boons-Prins et al., 1993) were used as initial crop parameters in the calibration process. For silage maize, crop parameters were calibrated in a similar way on yields of the best agricultural producers in the region, starting from values established by Vazifedoust et al. (2008).

At level 1, required daily grid weather data, i.e. minimum and maximum temperature, wind speed (at 10 m height), vapour pressure, rainfall and global radiation or sunshine hours, are generated through interpolation of daily weather data from weather stations. Daily weather data of 33 weather stations in and around the district (Figure 2) were used for estimation of daily weather characteristics in the grid cells. In preparing the weather data for use in the CGMS model, the following steps have been taken:

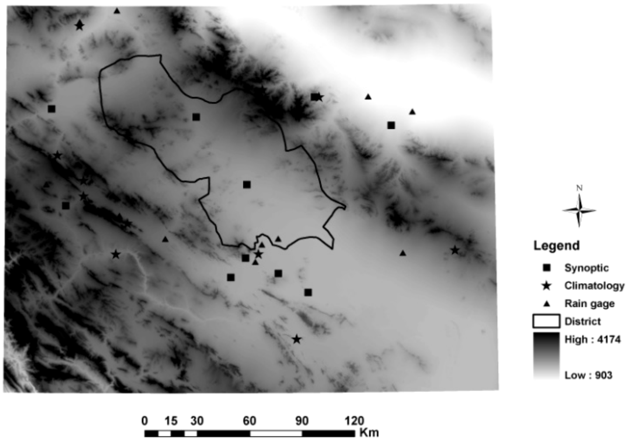


Figure 2. Location and type of weather stations in and around Borkhar & Meymeh district on DEM map.

Quality control of weather data

Quality of the daily weather data was checked manually. Wrong or improbable records were removed from the database. Missing values were then replaced by the average values, calculated in the next step.

Calculation of reference weather

Average weather characteristics for each day in each station during the recorded period were calculated by the "Reference Weather" package, developed by the Joint Research Center (JRC, 2004). The missing values in the daily weather records of the weather stations were replaced by the calculated average values.

Calculation of Ångstrom and Hargreaves coefficients

Solar radiation is one of the important weather characteristics in crop growth simulation, as it provides energy for photosynthesis and evapotranspiration (Donatelli et al., 2003; Pohlert, 2004). Solar radiation has been measured in only three of the weather stations (Esfahan, Najaf Abad & Kaboutar Abad), used in this analysis. Ångstrom (1924) and Hargreaves

(Hargreaves et al., 1985) coefficients for calculating solar radiation from sunshine duration and temperature have been derived for these stations (Farhadi Bansouleh et al., 2009). Coefficients for the other weather stations were estimated through interpolation of the coefficients in these three weather stations, using the “Supit constants” package (JRC, 1997).

Calculation of additional environmental characteristics

In this step, daily values of E_0 (Evaporation from a free water surface), ES_0 (Evaporation from wet bare soil) and ET_0 (Potential evapotranspiration of reference crop) are calculated for all stations. E_0 and ES_0 are calculated by the Penman equation (Penman, 1948), while ET_0 is calculated by the Penman-Monteith equation (Allen et al., 1998). Solar radiation was calculated by either the Ångstrom or the Hargreaves equation, depending on data availability.

Calculation of grid weather data

Daily weather data in the grid cell centers for the period 1985-2004 were generated through interpolation of the daily weather data of the most similar weather stations (Van der Goot et al., 2004). Similarity between grid cells and weather stations were determined based on the distance between grid cell center and weather station, Average altitude of the agricultural area in the grid cell.

CGMS has the capability to apply the crop growth simulation models (at level 2) spatially by their application at different points. For this purpose, the area of interest should be divided into homogeneous units, in this study the EMUs, to each of which WOFOST is applied in the CGMS system. WOFOST simulates phenological development, leaf area development and aboveground dry matter accumulation of annual field crops from emergence (or sowing) to maturity in daily time steps, based on daily weather data, soil properties and crop characteristics. Crop growth rate depends on daily net CO_2 assimilation rate, calculated as a function of intercepted light, which is determined by the level of incoming radiation and the leaf area of the crop. From absorbed radiation and the photosynthetic characteristics of single leaves, the daily rate of potential gross photosynthesis is calculated. The assimilation, after subtraction of respiration, is partitioned over the various plant organs, i.e. leaves, roots, stems and storage organs. WOFOST simulates crop production in two production situations (potential and water-limited, while the nutrient-limited situation is mimicked through calculation of the influence of nitrogen, phosphorus and potassium availability on yield on an annual basis. In CGMS, only the potential and water-limited situations are considered. Potential yield of a crop is only dependent on weather (solar radiation and temperature) and crop characteristics (Boogaard et al., 1998). Water-limited yield is also dependent on weather characteristics (solar radiation, temperature, rainfall, humidity and wind speed), soil physical characteristics and irrigation regime. In this paper focus is on the potential production situation and therefore only results in the potential situation are presented.

Starting point of crop growth simulation is either sowing or emergence date of the crop, which can vary among grid cells. Sowing date in the region depends on weather, cropping system and availability of agricultural machinery. Winter crops in the study area are sown in October (winter barley) and November (winter wheat), with a variation of some days among grid cells. In grid cells where two crops per year can be cultivated, winter crops are assumed to be sown 20 days earlier than those in grid cells with a single crop. Summer crops in the double cropping system are sown after harvest of the winter crops (or following the last irrigation of winter crops, when the summer crop is cultivated on other parcels). Crop growth duration of winter crops is longer, the lower the temperature in the grid cell. Therefore, in these grid cells, cultivation of a second crop in the year is not possible, because of late harvest of winter crops. To take into account that effect, the region has been classified into three zones (Table 1), based on average annual temperature, latitude and altitude of the grid cells. For each zone, a cropping calendar has been defined per crop and cropping system (Table 2).

Table 1. Number of villages, average characteristics and area of the cropping calendar zones in Borkhar & Meymeh district.

Zone	Number of villages	Annual temperature (^{o}C)	Altitude (m)	Latitude (^{o}N)	Area of EMUs	
					ha	%
R_1	26	16.1	1610	32.91	55269	86.3
R_2	13	13.1	1932	33.35	7143	11.2
R_3	8	11.1	2277	33.43	1616	2.5
Total	47				64028	100

Table 2. Emergence date of CGMS-crops in the single and double cropping systems per cropping calendar zone.

Crop	Cropping system	Cropping calendar zone	Emergence date
Winter wheat	Single	R_1, R_2	21 Nov
Winter wheat	Single	R_3	1 Dec
Winter wheat	Double	R_1	1 Nov
Silage Maize	Single	R_1	11 Apr
Silage Maize	Single	R_2	21 Apr
Silage Maize	Single	R_3	1 May
Silage Maize	Double	R_1	1 July

Results and Discussion

Growth of winter wheat and silage maize has been simulated based on 20 years daily weather data (1985-2004) for 128 EMUs delineated in Borkhar & Meymeh district using CGMS. Potential crop yield and water requirement are not related to soil characteristics. Therefore, potential water requirements per decade of the winter wheat and silage maize have been calculated in the 47 grid cells of Borkhar & Meymeh district based on daily weather data for the years 1985-2004 and CGMS outputs in the potential situation. Crop water requirements for the double cropping systems have been calculated only for zone R_1, where double cropping is possible. Total crop water requirements per growing season and maximum crop water requirements per decade have been calculated for each crop per grid cell and for each year. These characteristics vary both, spatially and temporally, because of spatial and temporal variation in weather conditions.

Average seasonal water requirements of winter wheat and silage maize in the potential situation and single cropping system for the years 1985-2004 were in the range 410-553 and 528-634 mm, respectively in different grid cells (Figure 3) Crop water requirements are highest in the grid cells at higher latitudes and altitudes, characterized by lower temperatures. Simulated crop cycles are longer in the grid cells located in zones R_2 and R_3 than in those in zone R_1 (Table 3). Average seasonal water requirements of crops in zones R_2 and R_3 exceed those in R_1 and in single cropping systems exceed those in double cropping systems (Table 4). The lower variability in crop water requirements in double cropping systems (Figure 3). is associated with (i) differences in sowing dates of single and double crops and (ii) the highest crop water requirements in single crops are observed in zones R_2 and R_3 with longer crop growth cycles. In these zones, double crops cannot be cultivated, hence, the variability for double crops is based on one zone, while that for single crops refers to the entire district (three zones).

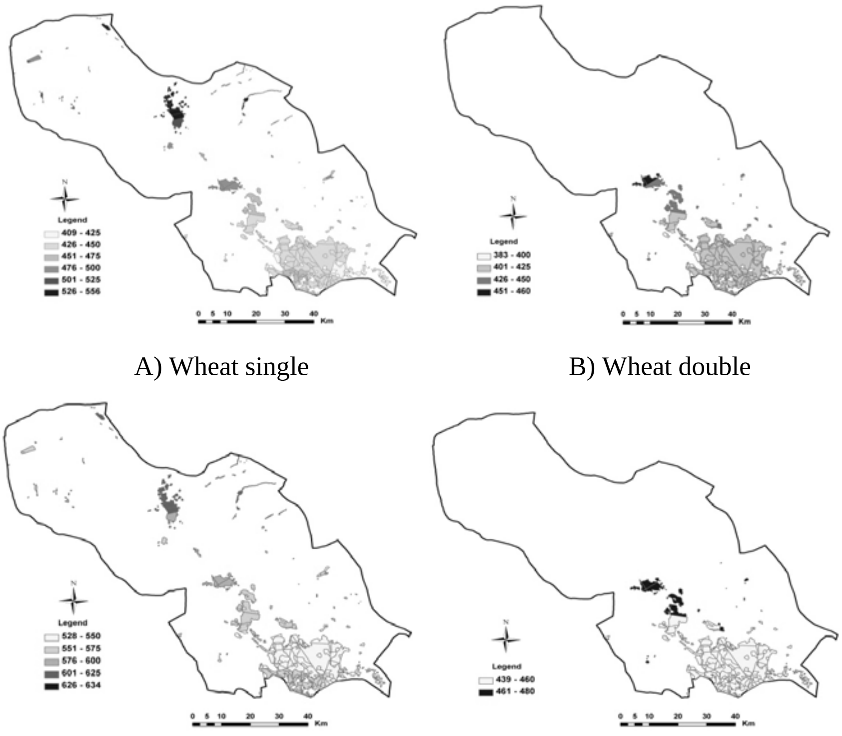
Table 3. Average length of the growing period (days) of the crops in zones R_1, R_2 and R_3.

Crop	Cropping system	R_1	R_2	R_3
Wheat	Single	205	227	234
	Double	216	-	-
Silage maize	Single	106	113	124
	Double	91	-	-

Table 4. Average simulated water requirements in the potential production situation of crops in single and double cropping systems in the three cropping calendar zones (mm).

Crop	R_1	R_2	R_3
Wheat Single	442	521	512
WheatDouble	412	-	-
Silage Maize single	551	596	589
Silage Maize double	449	-	-

Timing and magnitude of maximum water requirements per decade are important criteria for agricultural planners and irrigation designers. As these characteristics vary spatially (i.e. are different for different grid cells), three grid cells (villages) have been analyzed in more detail, each one representative for one of the cropping calendar zones (Figure 4). The villages of Sin and Ghasem Abad are located in the central part of zone R_1 and R_2, respectively. For zone R_3, the village Laibid has been selected randomly, as selecting a village in the center was not possible. Average potential evapotranspiration of the 'reference crop' (ET_0), calculated based on generated grid weather data is lower for Laibid than for the other two villages, while in Sin it is higher than in the other two villages in the first half of the year (Figure 5). ET0 in the period of January until June is higher in Sin than in Ghasem Abad, while the situation is reverse in the remainder of the year.



A) Wheat single B) Wheat double

C) Silage maize single D) Silage maize double

Figure 3. Average, for the period 1985-2004, calculated potential seasonal water requirements (mm) for winter wheat, silage maize in the single and double cropping systems in the villages of Borkhar & Meymeh district.

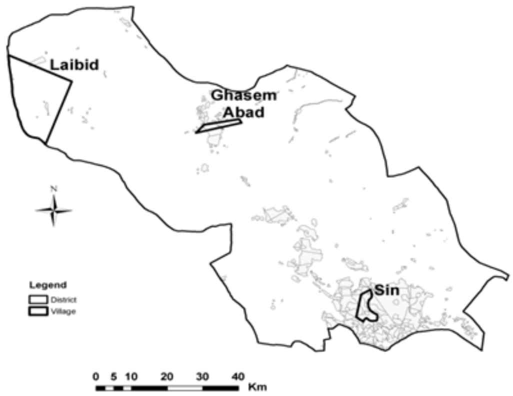


Figure 4. Location of selected grid cells/villages in Borkhar & Meymeh district for analysis of water requirements in different cropping zones.

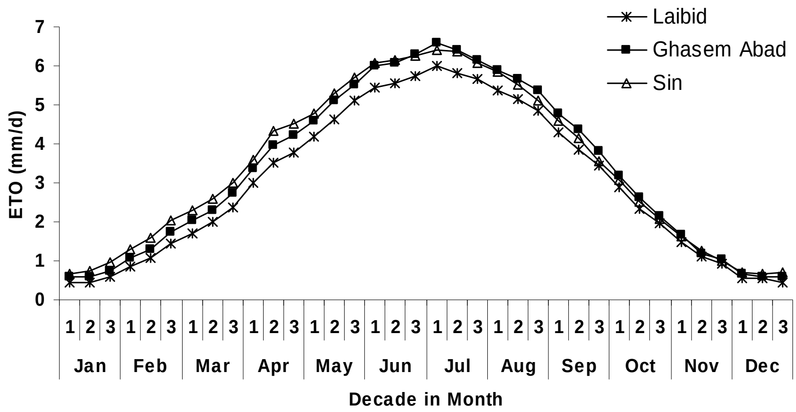


Figure 5. Calculated potential evapotranspiration of reference crop (ETO) in the selected villages of Borkhar & Meymeh district.

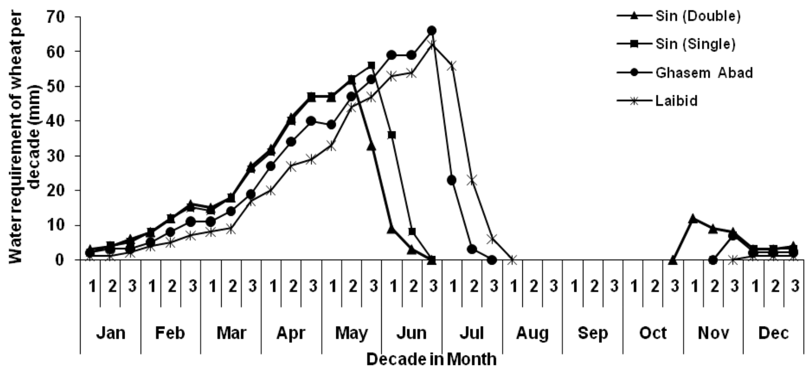
Maximum water requirements per decade (Figure 6) of winter wheat in Sin (last decade of May, 56 mm) are lower than in Ghasem Abad (last decade of June, 66 mm) and in Laibid (last decade of June, 62 mm). Thus, water requirements for wheat are lower in R_1 than in R_2 and R_3, while average temperatures in R_1 are higher. The consequence is that the crop cycle is longer in R_2 and R_3 than in R_1. Therefore, the final part of the growing seasons in R_2 and R_3 is in the warmer period, associated with higher evapotranspiration.

Maximum water requirement of silage maize in Sin is in the first decade of July, compared to the last decade of July in Ghasem Abad and Laibid. Although total seasonal water requirements of silage maize vary among grid cells, differences in the patterns of water requirement are negligible. At the time that ET_0 is high, silage maize in all grid cells fully covers the soil and exhibits maximum evapotranspiration. As there is no rainfall during the growing period of summer crops, water requirements of summer crops are equal to potential evapotranspiration.

The inter-annual variation in ET_0 originates from variation in weather conditions, which also causes variations in potential evapotranspiration of other crops. The coefficient of variation of seasonal water requirements over the period 1985-2004 is higher for winter crops than for summer crops (Figure 7). The larger variation in water requirements for winter crops might be associated with the inter-annual variation in contribution of rainfall. Rainfall is quasi-absent during the growth period of summer crops and the variation in water requirements of these crops is related to variation in other weather characteristics. The coefficient of variation in water requirements in zone R_3 is smaller than in zones R_1 and R_2. The temporal variation in crop water requirements is thus substantial, which is the result of the temporal variability in weather conditions.

Conclusions

Results of spatial analysis of biophysical resources indicate that potential crop water requirements show significant spatial and temporal variation. Moreover this characteristic varies significantly for single and double cropping systems. Although, the aim of this study was to simulate potential crop water requirement spatially, but the type of analysis that has been carried out in this study can support irrigation managers, agricultural planners and decision makers in other aspects such as:



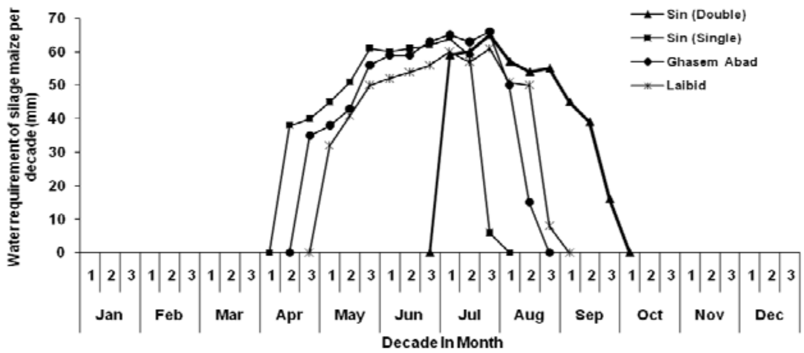


Figure 6. Average (1985-2004) simulated water requirements in the potential production situation of winter wheat, silage maize per decade in the villages of Sin (single and double cropping systems), Ghasem Abad and Laibid in Borkhar & Meymeh district.

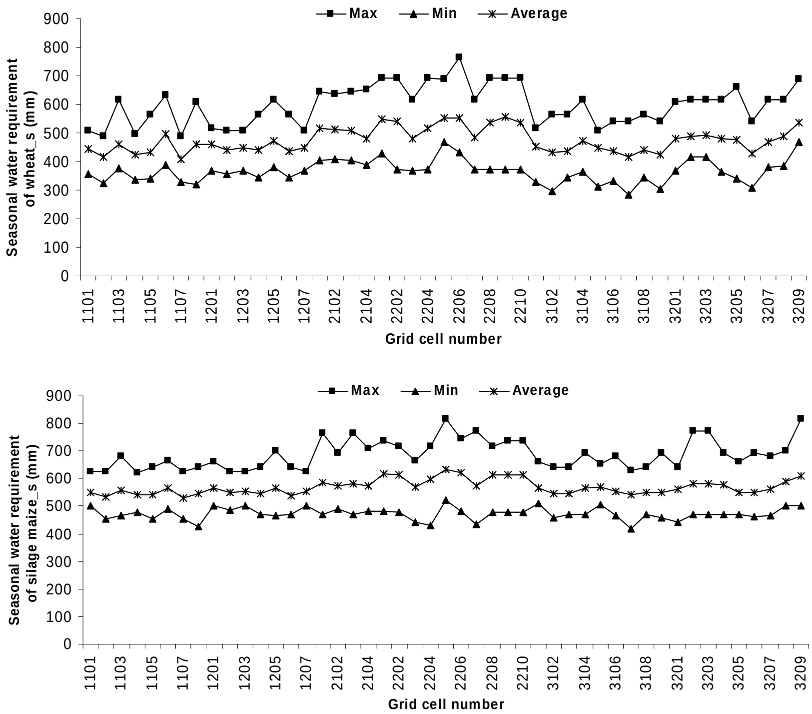


Figure 7. Minimum, maximum and average water requirements for the period 1985-2004 of winter wheat and silage maize (in single cropping systems) in different grid cells in Borkhar & Meymeh district.

Assessment of the feasibility of double cropping systems in each of the distinguished EMUs

In the current study, a summer crop has been simulated, following maturity of the winter crop, where the two growth cycles could be combined. This analysis has shown that in some parts of the study area a double cropping system can be accommodated, in other parts not (results not shown). The results of this study show that potential crop water requirements of double crops are different from those of single crops, because of differences in sowing date and consequently in growing periods.

Estimation of spatial crop water requirements per decade

Results of the present study have shown that seasonal crop water requirements and maximum water requirements per 10-day period spatially vary in the district. This spatially explicit information can be used in support of allocation of water resources in situations of water shortage.

In other hand, the model system applied in the current study has limitations that influence its (potential) applicability as follows:

Agro-ecological models include many parameters

For simulation of crop growth, WOFOST uses around 45 crop-specific characteristics, some of which are defined as a function of crop development stage. Since our understanding of crop growth and development is partial at best and moreover parts of the crop characteristics are variety-specific, some of these crop characteristics have to be calibrated and validated based on results of site-specific field experiments. Identifying appropriate values for crop characteristics is neither a trivial nor an easy task, even when results of local field experiments are available.

Field experiments are required to generate information for calibration and validation of crop parameters

These experiments are costly and time-consuming. For calibration and validation of CGMS, detailed crop data and other information at different growth stages are required.

The crop growth simulation model WOFOST, implemented in CGMS, also has some limitations

WOFOST is a purely biophysical model and does not take into account impacts of diseases, pests, crop sequences (crop rotations) and agricultural management on crop growth. Moreover, the model does not calculate crop evapotranspiration directly, but that has to be calculated post-model, based on model-calculated potential transpiration, reference crop evapotranspiration and leaf area index.

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